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Deuterium at High Redshifts: Recent Advances and Open Issues

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Abstract. Among the light elements created in the Big Bang, deuterium is one of the most difficult to detect but is also the one whose abundance depends most sensitively on the density of baryons. Thus, although we still have only a few positive identifications of D at high redshifts—when the D/H ratio was close to its primordial value—they give us the most reliable determination of the baryon density, in excellent agreement with measures obtained from entirely different probes, such as the anisotropy of the cosmic microwave background temperature and the average absorption of the UV light of quasars by the intergalactic medium. In this review, I shall relate observations of D/H in distant gas clouds to the large body of data on the local abundance of D obtained in the last few years with *FUSE*. I shall also discuss some of the outstanding problems in light element abundances and consider future prospects for advances in this area.

1. Introduction and Historical Background

The measurement of the interstellar abundance of deuterium was one of the main science drivers of the *FUSE* mission right from its inception. Five years on, this promise has been amply fulfilled, as demonstrated by the numerous talks and posters at this meeting devoted to *FUSE* results on D/H.

The importance of deuterium stems from the fact that, among the light elements created in Big Bang nucleosynthesis (BBNS), it is the one whose primordial abundance responds most sensitively to cosmological density of baryons, $\Omega_{\rm b}$. While ^{4}He is the most abundant, because it soaks up essentially all the available neutrons, this property also makes it a rather insensitive 'baryometer'. The quantity $\Omega_{\rm b}$, or more precisely the baryon to photon ratio η, only affects $Y_{\rm p}$ (the primordial mass fraction in ^{4}He) by determining the time delay before BBNS can set in—and thus the time available for neutrons to decay—in the first few minutes of the universe history. The more fragile deuterium, on the other hand, is easily destroyed by two-body reactions with protons, neutrons and other nuclei so that its abundance relative to hydrogen when BBNS is over, $({\rm D/H})_0$ or D_0 for short, shows a steep, inverse, dependence on $\Omega_{\rm b}$. ^{7}Li is less useful than D in this respect because it is far less abundant, by about five orders of magnitude, and its dependence on $\Omega_{\rm b}$ is double-valued because it can be synthesised via different nuclear reactions in the high and low baryon density regimes.

The detection of interstellar D was among the first discoveries made by *FUSE*'s predecessor, the *Copernicus* satellite. Rogerson & York (1973) resolved the isotope shift in the Lyγ line seen towards the bright B1 III star β Centauri,

and deduced $N(\mathrm{D\ I})/N(\mathrm{H\ I}) = (1.4 \pm 0.2) \times 10^{-5}$. Three decades later, the mean of 21 measurements of D/H in the 'Local Bubble' (the nearby region of the Milky Way disk) is in excellent agreement with *Copernicus*' first detection: $\langle \mathrm{D/H} \rangle = (1.56 \pm 0.04) \times 10^{-5}$ (Wood et al. 2004).[1]

An important property of deuterium is that it is only destroyed whenever interstellar gas is cycled through stars (a process termed astration), so that its abundance relative to H steadily decreases with the progress of galactic chemical evolution. Analytically, this reduces to a simple expression for the time evolution of D:

$$(\mathrm{D/D_0}) \;=\; f^{(1/\alpha\ -1)} \;=\; e^{-Z(1/\alpha\ -1)} \qquad (1)$$

where f is the gas fraction, Z the metallicity (in units of the yield of a primary element such as oxygen) and α is the mass fraction which is locked up in long-lived stars and stellar remnants whenever a quantity M of interstellar matter is turned into stars (Ostriker & Tinsley 1975; Pagel 1997). Equation (1) is valid in the simplest case of a 'closed-box' model of chemical evolution. More realistic models which include inflow and/or outflow generally result in lower reductions of the primordial D/H as a function of either f or Z (Edmunds 1994). We cannot measure the lock-up fraction α directly, but only deduce it theoretically by assuming a distribution of stellar masses (the IMF) and guessing at what fraction of its initial mass each star returns to the interstellar medium (ISM).

In principle, the degree of astration suffered by D in the Milky Way, where $f = 0.1 - 0.2$, could be anywhere between 20% and 90%, depending on the uncertain value of α. Consequently, Rogerson and York could only use their measurement of D/H in the ISM today to place a lower limit on $(\mathrm{D/H})_0$ and a corresponding upper limit $\Omega_\mathrm{b} \leq 0.0675$ (for $h = 0.7$ where, as usual, h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. In this article I shall use $h = 0.7$ throughout and dispose of the h^2 term in the value of Ω_b). Note that the above upper limit on Ω_b, even without any correction for D astration, implies that most of the matter in the universe is non-baryonic.

2. Deuterium at High Redshifts

In parallel with the rapid advances in our knowledge of the Galactic interstellar medium made possible by the success of the *Copernicus* mission, the mid-1970s saw the burgeoning of QSO absorption line spectroscopy which extended similar lines of enquiry to the gas in galaxies and the intergalactic medium at much earlier times. Thanks to expansion of the universe, which redshifts the same ultraviolet transitions identified by *Copernicus* into the optical region, the interstellar media of distant galaxies which happen to lie in front of quasars could begin to be probed systematically, by capitalising on the light-gathering power of ground-based telescopes, as well as the efficiency and linearity of recently developed digital detectors. Adams (1976) was the first to point out that such

[1] An interesting observation is that the distance to β Cen has 'doubled' since 1973. The *Hipparcos* parallax to this star implies a distance $d = 161$ pc, while the parallactic distance available to Rogerson & York (1973) was $d = 81$ pc. This is a clear demonstration that it is easier for astronomers to measure chemical abundances than distances, even to the brightest stars.

observations were also likely to bring us closer to determining the primordial abundance of deuterium, since gas less chemically evolved than the local ISM should be more common at high redshift.

In the mid-1970s the practical difficulties of detecting D in QSO absorption line systems were daunting. The combined requirements of high spectral resolution (the isotope shift in the Lyman series amounts to $-82\,\mathrm{km\ s}^{-1}$), high sensitivity (even the brightest high redshift QSOs are more than a million times fainter than β Cen), and wide wavelength coverage (so as to record several Lyman lines at once) could not be met for another twenty years, until the advent of echelle spectrographs on 8-10 m class telescopes. Even with these technological advances, however, isolating D at high z remains an intrinsically difficult observation due to (a) the high density of H absorption lines in the Lyα forest (see Figure 1) and (b) the paucity of QSO absorption systems with a sufficiently simple velocity structure to resolve cleanly D I absorption blueshifted by $82\,\mathrm{km\ s}^{-1}$ from its corresponding H I. All but a few percent of either Lyman limit systems (LLS), absorbers with column densities $N(\mathrm{H\ I}) \gtrsim 3 \times 10^{17}\,\mathrm{cm}^{-2}$, or damped Ly$\alpha$ systems (DLAs) with $N(\mathrm{H\ I}) \geq 2 \times 10^{20}\ \mathrm{cm}^{-2}$, exhibit multiple velocity components spanning more than $100\,\mathrm{km}^{-1}$. And yet these two classes of QSO absorbers, at the high end of the power-law distribution of H I column densities, are the ones which can be realistically targeted in D searches, given that the primordial abundance of D is likely to be of the order of a few times 10^{-5}.

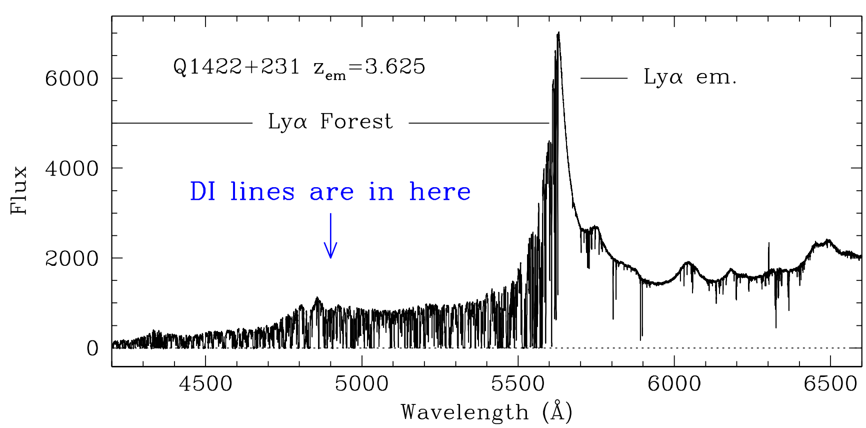

Figure 1. High resolution spectrum of a typical high redshift QSO (reproduced from the work of Ellison et al. 2000). At redshifts $z > 2$ it becomes progressively more difficult to distinguish D I absorption from the hundreds of absorption lines which make up the Lyα forest.

These obstacles partly explain why, ten years after the first detection of D in a high redshift QSO absorber by Tytler et al. (1995), the number of measurements generally regarded as reliable is disappointingly low (see Figure 2). Averaging the five published values of (D/H) obtained from D lines which are at least partially resolved (Kirkman et al. 2003), Steigman (2004) deduced $\langle(\mathrm{D/H})_0\rangle = (2.6 \pm 0.4) \times 10^{-5}$ (the error quoted is $\sigma/\sqrt{5}$). This is likely to be the primordial value, since all five absorption systems originate in gas of low

metallicity—1/30 of solar or less (see Figure 2)—where according to equation (1) the astration of D should have been insignificant. Using the scaling of $(\mathrm{D/H})_0$ with η and Ω_b given by Burles, Nollett, & Turner (2001), $(\mathrm{D/H})_0 = (2.6 \pm 0.4) \times 10^{-5}$ implies $\Omega_\mathrm{b} = (0.044 \pm 0.004)$.

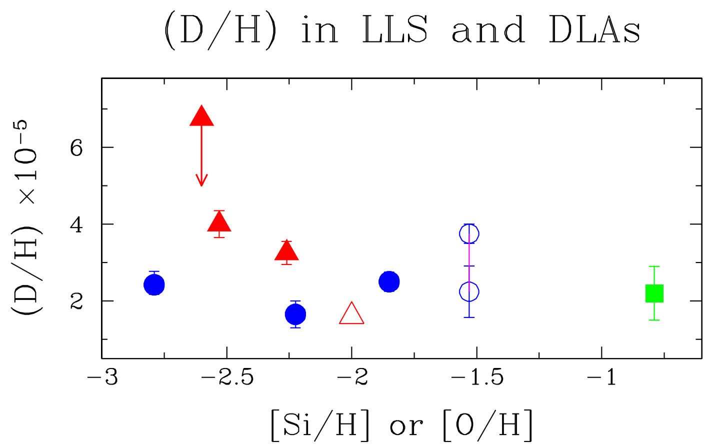

Figure 2. Compilation of D/H measurements in QSO absorbers (as of August 2004). Triangles denote measurements in Lyman limit systems, while circles are for damped Lyα systems. Filled symbols are used for cases where the D I absorption is at least partially resolved (O'Meara et al. 2001; Kirkman et al. 2003; Pettini & Bowen 2001). Open symbols indicate absorption systems with more complex velocity structure which renders the determination of D/H less straightforward (open triangle: Crighton et al. 2004; open circles: D'Odorico, Dessauges-Zavadsky, & Molaro 2001; Levshakov et al. 2002). The two open circles refer to two analyses of the same absorber, at $z_\mathrm{abs} = 3.02486$ in Q0347−383, and illustrate the uncertainty in D/H resulting from different interpretations of the multi-component character of the absorption lines. For this reason, the currently favoured value of $(\mathrm{D/H})_0$ is generally taken to be the weighted mean of the five detections indicated by the filled triangles and circles (see text). The filled square shows, for comparison, the *FUSE* measurement by Sembach et al. (2004) of D/H in Complex C, a high Galactic latitude concentration of H I which is thought to be relatively unprocessed gas being accreted by the Milky Way. Plotted on the x-axis is the abundance of either Si or O in the absorber in the customary notation whereby $[\mathrm{Si/H}] = \log(\mathrm{Si/H})_\mathrm{abs} - \log(\mathrm{Si/H})_\odot$. All high redshift QSO absorbers where D/H has been measured are chemically unevolved systems, with metallicities of less than $\sim 1/30$ of solar.

3. Other Measures of Ω_b

Recent years have seen spectacular advances in the determination of a number of fundamental cosmological parameters, including Ω_b. In particular, the *WMAP* satellite and other experiments have now mapped with high precision the temperature anisotropies in the cosmic microwave background (CMB) over a range of angular scales which includes the first few peaks in the power spectrum. Their relative amplitudes vary with Ω_b, as can be seen from Figure 3.

The physical reason for this is that the baryon density determines the inertia in the photon-baryon fluid. Higher values of $\Omega_{\rm b}$ result in deeper compressions and less pronounced rarefaction; thus the compressional peaks (the odd-numbered ones) are hotter, while the rarefaction peaks (even numbered) are cooler (Page et al. 2003). The best fit to the CMB temperature angular power spectrum is obtained for $\Omega_{\rm b} = (0.045 \pm 0.002)$ (Spergel et al. 2003) in near-perfect agreement with the value implied by the primordial abundance of deuterium. Sometimes we take our achievements for granted. The fact that we can measure the cosmological density of ordinary matter in two totally independent ways—one based on a set of nuclear reactions which took place in the first few minutes in the existence of our universe, the other on the acoustic oscillations in the mix of photons, dark matter and baryons which became imprinted on the microwave sky some 380 000 years later—and get the same answer is a spectacular success of modern observational cosmology and gives us confidence in the validity of the entire framework.

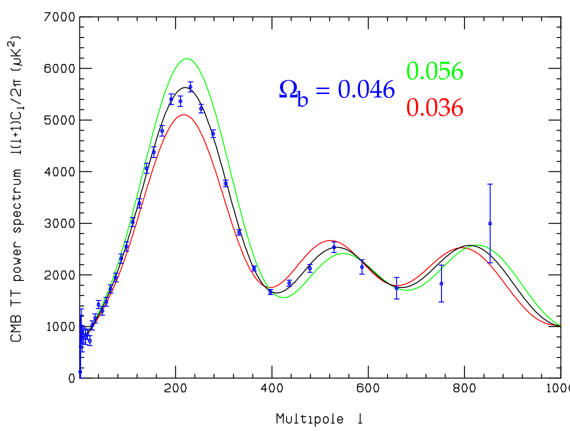

Figure 3. The data points are the temperature anisotropies in the cosmic microwave background measured by the *WMAP* satellite. The variance of the multipole amplitude is plotted vs. multiple number ℓ (the angular scale on the sky corresponding to multipole ℓ is $\theta \sim 200^\circ/\ell$). The continuous curves show the sensitivity of the power spectrum to $\Omega_{\rm b}$, while keeping all other relevant cosmological parameters fixed. (Figure reproduced from Steigman 2004).

The average flux decrement in the Lyα forest, measured by the parameter DA first introduced by Oke & Korycansky in 1982 (see Figure 4), is also sensitive to the baryon density. The recent comprehensive analysis by Tytler et al. (2004) arrived at a best estimate $DA(z = 1.9) = 0.151 \pm 0.007$ in the interval $1070 < \lambda_0 < 1170$ Å, or $DA(z = 1.9) = 0.12 \pm 0.01$ after correcting for metal lines, LLS and DLAs. Hydrodynamic simulations can reproduce this value of DA if $\Omega_{\rm b} = 0.044 \pm 0.002$.

4. Implications

The excellent agreement between the three independent determinations of $\Omega_{\rm b}$ discussed above could reasonably be taken as evidence that this cosmological

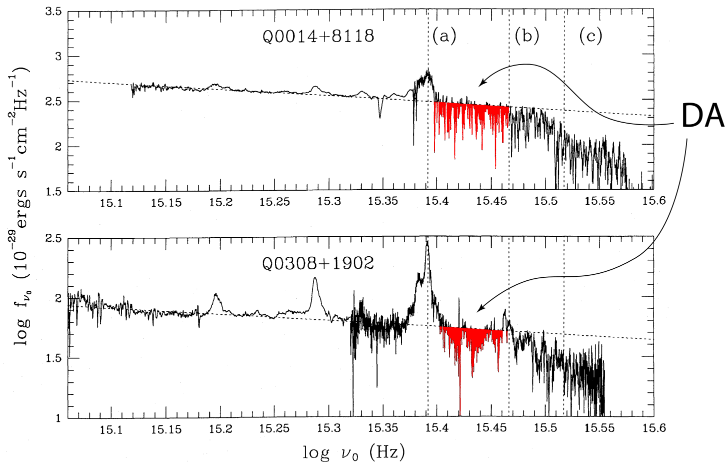

Figure 4. The parameter *DA* measures with a single number the average opacity of the Lyα forest. Hydrodynamic simulations of the intergalactic medium show that the value of *DA* depends on the combination of the mean gas density ($\Omega_{\rm b}$), the density fluctuations (the parameter σ_8), and the intensity of the ionising background. The two QSO spectra shown here are from the survey by Steidel & Sargent (1987).

parameter is now known to better than 10%. However, in order to be confident that this is indeed the case, it is important to carry out as many consistency checks as possible by considering the consequences of adopting $\Omega_{\rm b} = 0.044$.

4.1. Is the Degree of Astration of D Plausible?

Adopting the value D/H = $(1.56 \pm 0.04) \times 10^{-5}$ from Wood et al. (2004) as representative of the D abundance in the local interstellar medium, and a primordial $({\rm D/H})_0 = (2.6 \pm 0.4) \times 10^{-5}$ (Steigman 2004) implies that less than 50% of the D created in the Big Bang has been destroyed through the entire chemical evolution history of the Milky Way Galaxy. In our simple 'closed-box' model where $(D/D_0) = f^{(1/\alpha\ -1)}$, $(D_{\rm ISM}/D_0) = 0.60$ in turn implies $\alpha \simeq 0.75 - 0.8$ (for $f = 0.2 - 0.1$). As pointed out by Edmunds (1994), a value of α in this range is consistent with expectations for a Salpeter IMF, using a back-of-the-envelope accounting whereby all stars less massive than the Sun have not returned any baryons to the interstellar medium over the lifetime of the Galactic disk and all stars more massive than the Sun leave behind $1\,M_\odot$ remnants at the end of their lives. More complex chemical evolution models, including infall onto the Milky Way disk, can also accommodate this degree of astration within the current picture of the assembly of the Galaxy and its past history of star formation (e.g. Tosi et al. 1998; Prantzos & Ishimaru 2001; Romano et al. 2003).

Questions remain, however, as to whether the D/H ratio measured by Wood et al. (2004) in the Local Bubble is representative of the true Galactic deuterium abundance—a topic which was debated extensively at this meeting. Doubts are raised by our inability to find a straightforward explanation for the unexpectedly large scatter in the values of D/H revealed by *FUSE* observations of stars beyond ~ 100 pc from the Sun. Differing interpretations which have been put forward

include selective depletion of D onto grains (see J. Linsky's and B. Draine's contributions to this volume) and recent infall of chemically unenriched gas onto the solar neighbourhood (see G. Hébrard's article). In the former case it is advocated that the *highest* measures of D/H are the representative ones, since presumably they suffer the lowest amount of dust depletion, and the true (gas+dust) value of $(D/H)_{ISM}$ could then be as high as 2.3×10^{-5}. It remains to be established whether levels of astration as low as 10–15% are plausible for the Milky Way. In the latter case, it is argued that the low measures of D/H (and D/O—see Hébrard & Moos 2003) over the larger areas of the disk which lie beyond the Local Bubble more closely reflect the consumption of D over the chemical history of the Galaxy; in this case $(D/H)_{ISM} \simeq (0.5 - 1) \times 10^{-5}$ and $D_{ISM}/D_0 \simeq 0.2 - 0.4$. The lower limit of this range may require strong gas outflows to have taken place during the early evolution of the Milky Way, a scenario which now seems unlikely (Edmunds 1994; Prantzos & Ishimaru 2001).

Although five years of *FUSE* observations have provided us with a wealth of new data on the D/H ratio in the local ISM, it is very frustrating that the full picture still eludes us. A possible way out of this impasse may be to target distant stars whose sight-lines are known to exhibit widely different degrees of interstellar dust depletions. A correlation (or absence of one) between the D/H ratio and the gas-phase abundances of the most depleted elements, such as Fe and Ti, may be the clue which we are still missing.

4.2. Tension with the Abundances of Other Light Elements

While the primordial abundance of D agrees with the most likely estimates of Ω_b from the CMB and the Lyα forest opacity, those of ^{4}He and ^{7}Li apparently do not (see Figure 5). Perhaps the idea that Y_p (the primordial mass fraction in ^{4}He) can be used as a precise baryometer is too optimistic. While the fact that approximately one quarter of the baryons is in the form of ^{4}He is one of the pillars of the standard Big Bang model, knowing now that $\Omega_b = 0.044$ shows just how insensitive Y_p is to the precise value of Ω_b. Once we are on the flat part of the Y_p vs. Ω_b curve (see Figure 5), we are vulnerable to subtle systematic errors in the determination of the helium abundance in H II regions—and its extrapolation to zero metallicity—which may be very difficult to overcome (e.g. Peimbert et al. 2003). Olive & Skillman (2004) have recently re-examined the problem and proposed a non-parametric approach whereby the physical parameters (in particular the nebular electron temperature, the optical depth of the emission lines, and underlying stellar absorption) which enter in the determination of the helium abundance are derived in a self-consistent way solely from the relative ratios of He and H emission lines. Their main conclusion is that previous analyses have largely underestimated the systematic uncertainties in the determination of Y_p and that even the best data available at present cannot constrain Y_p to better than 0.249 ± 0.009. While this relieves the 'tension' with D_0, it also raises questions as to whether we can ever pin down the primordial helium abundance to the degree of accuracy required to test concordance with other light elements.

The situation is even worse for ^{7}Li whose abundance in the most metal-poor stars of the Galactic halo exhibits a narrow range (the well-known 'Spite plateau') which is approximately three times lower than the primordial value expected for $\Omega_b = 0.044$ (Ryan et al. 2000). A number of possible explanations

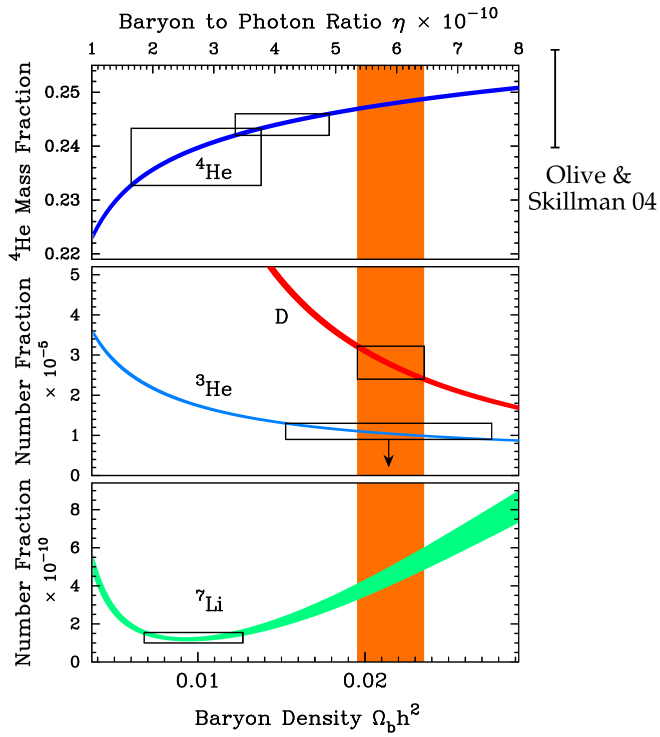

Figure 5. Observed and predicted primordial abundances of light elements created in BBNS (Figure reproduced from Kirkman et al. 2003). The vertical band shows the values of $Y_{\rm p}$ and $(^7{\rm Li/H})_0$ expected for $\Omega_{\rm b} = 0.044$ [the value implied by $({\rm D/H})_0$]. Current estimates of $Y_{\rm p}$ by Olive, Steigman, & Skillman (1997), shown by the larger box in the top panel, and by Izotov & Thuan (1998) (smaller box) fall short of the expected value of $Y_{\rm p}$. This may well be due to underestimated systematic errors, as proposed by Olive & Skillman (2004) who argue for a wider range of possible values of $Y_{\rm p}$, indicated by the error bar on the right-hand side of the Figure. The narrow box in the bottom panel shows the location of the 'Spite plateau', the narrow range of ^{7}Li abundances measured in old, metal-poor stars in the Galactic halo by Ryan et al. (2000), and which is also well below the expected value of $(^7{\rm Li/H})_0$.

have been considered, including uncertainties in the effective temperatures of the stars (e.g. Bonifacio et al. 2002), Li depletion in their atmospheres through mixing with material from the stellar interior (e.g. Pinsonneault et al. 2002), and errors in the relevant nuclear reaction rates (Coc et al. 2004). None of these, however, is fully convincing. Naively one would expect the first two effects to result in a dispersion of the Li abundances in metal-poor stars—in contrast with the narrow range observed, while the third would require the rate for the $^7{\rm Be}(d,p)2\ ^4{\rm He}$ reaction (which competes with $^7{\rm Be}(n,p)^7{\rm Li}$ for the destruction of ^{7}Be) to be revised upwards by more than two orders of magnitude.

In conclusion, if D_0, the CMB power spectrum, and the Lyα forest average transmission give us the correct value of $\Omega_{\rm b}$—as seems likely given the concordance of these three very different methods—we are left with an internal tension between the abundances of the light elements created in BBNS. For ^{4}He we

can appeal to systematic uncertainties in the measurements, but ^{7}Li remains a puzzle.

5. Looking Ahead

The convergence of different methods upon the same value of Ω_b naturally raises the question as to whether it is worthwhile searching for additional QSO absorption systems where the primordial abundance of D may be measured, especially given the considerable investment in telescope time required. In my view this is still an important goal, as I now explain.

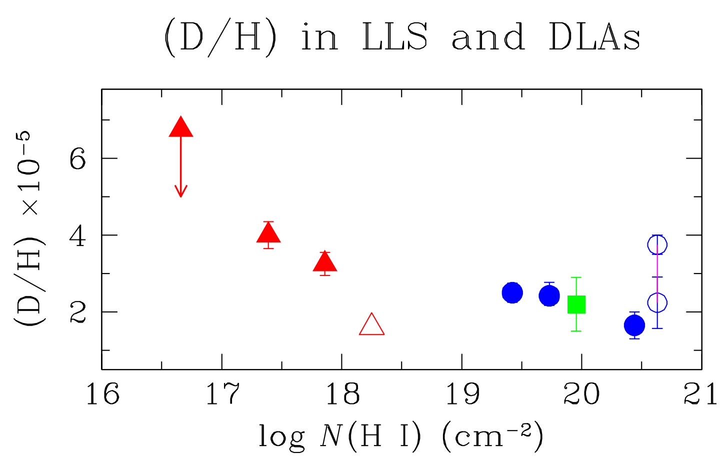

Figure 6. D/H measurements in QSO absorbers plotted against neutral hydrogen column density. The symbols have the same meaning as in Figure 2. There is a hint that D/H may be lower in DLAs (filled circles) than in LLS (filled triangles), but more D detections are required to establish whether the trend is real or merely a statistical coincidence.

The first point is that the dispersion among the five measurements of D/H which are considered most reliable in Figure 3 is higher than expected from their errors. This is not an unusual situation in astronomy, and the natural conclusion would be that the errors on the individual measurements have been underestimated, were it not for the fact that measures of D/H in the Galactic interstellar medium also show a dispersion which, as discussed above, is now thought to be real. Neither of the explanations put forward for the local dispersion —dust depletion and chemical inhomogeneities—are likely to apply to the high redshift absorption systems which are significantly metal- and dust-poor (e.g. Pettini et al. 1997a,b). Nevertheless, until the source(s) of variation—at both high and low redshift—are identified, we cannot be totally confident of our measurement of D_0.

As an illustration of this, the data in Figure 2 are replotted in Figure 6 as a function of neutral hydrogen column density N(H I) to show that, among the five measurements considered to be most reliable, there is a hint of a trend with N(H I), in the sense that D/H is lower in DLAs than LLS. This trend could be totally spurious, and a single future measurement could show it to have been

simply an artifact of the small number statistics. On the other hand, one can certainly think of reasons why LLS may give systematically higher estimates of D/H. The chances of contamination with hydrogen interlopers increase roughly as $1/N(\text{H I})^{0.5}$ (given that the number density of Lyα forest lines per unit column density interval scales as $N(\text{H I})^{-1.5}$, and are therefore lower for DLAs with $N(\text{H I}) \geq 2\times10^{20}$ cm^{-2} than for LLS with $N(\text{H I}) \geq 3\times10^{17}$ cm^{-2}. Furthermore, the measurement of $N(\text{H I})$ is more straightforward in DLAs, where it relies on fitting the profile of the damping wings of the Lyα absorption line, than in optically thick LLS where one has to fit simultaneously a large number of saturated Lyman series lines. Possibly, then, the values of D/H in DLAs should be given a higher weighting than those in LLS in order to obtain the best estimate of the primordial D abundance. I am not advocating such a course of action here, but simply pointing out that additional measurements of D/H in QSO absorption line systems at high z are required to exclude (or confirm) this possibility.

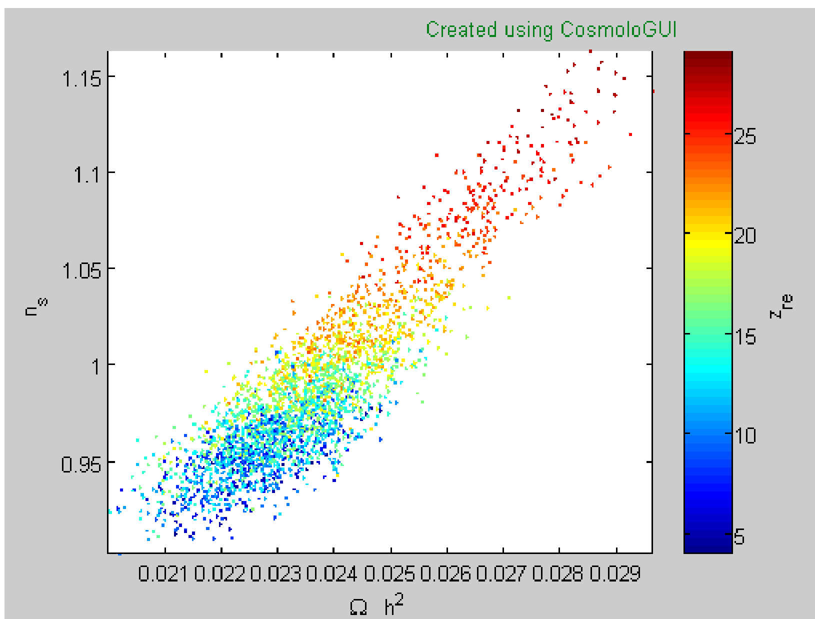

Figure 7. Interdependence of $\Omega_{\rm b}$ on other cosmological parameters—in this case the power-law index of primordial fluctuations n_s and the redshift of reionisation $z_{\rm re}$. All the combinations considered here give acceptable fits to the *WMAP* temperature (TT) and temperature-polarization (TE) angular power spectra. (Reproduced from http://www.ast.cam.ac.uk/∼sarah/cosmologui).

A second, and perhaps more fundamental, point is that among the various avenues which lead to the determination of $\Omega_{\rm b}$, the primordial abundance of deuterium is the most straightforward one, since it measures a combination of only two cosmological parameters, $\Omega_{\rm b}$ and H_0^2. In contrast, other methods generally measure combinations of several such parameters. In Figure 3, Gary Steigman showed the dependence upon $\Omega_{\rm b}$ of the amplitudes (and locations) of the acoustic peaks of the CMB angular power spectrum *by keeping fixed all other relevant parameters at their most likely values.* In contrast, Figure 7 shows the

interdependence of the baryon density Ω_b, the power-law index of primordial fluctuations n_s, and the optical depth to Thomson scattering which determines the redshift of reionisation. Now we see that the CMB value of $\Omega_b = (0.045 \pm 0.002)$ corresponds to the 'best' solutions for $n_s = 0.93$ (a nearly scale-invariant spectrum of fluctuations) and $z_{re} = 17$ (see Spergel et al. 2003), but that other combinations of these parameters are in fact admitted. Similarly, the Lyα forest optical depth method of Tytler et al. (2004) determines simultaneously Ω_b, σ_8 (the rms mass density fluctuation averaged over $8h^{-1}$ Mpc spheres), and the ionisation rate of hydrogen at a given redshift. It follows, then, that if we knew Ω_b with confidence from the primordial abundance of deuterium, we would be able to narrow down the allowed parameter space for other important cosmological quantities, and this is in itself strong motivation for improving the still very limited statistics on D/H at high z. The Sloan Digital Sky Survey will, when completed, more than double the known number of DLAs (e.g. Prochaska & Herbert-Fort 2004). I expect that, with perseverance, it will be possible to identify in that treasure-trove of spectra several new absorption systems suitable for the determination of D_0.

6. Summary

We have come a long way since that pioneering measurement by Rogerson & York of the interstellar abundance of deuterium with *Copernicus* more than thirty years ago. The number of such measurements now approaches fifty, thanks in particular to the capabilities of *FUSE* and the GHRS and STIS instruments on the *Hubble Space Telescope*. With large ground-based telescopes we have been able to probe high redshift clouds where D is still close to its primordial abundance. New methods have been exploited to determine the density of baryons, the most impressive of which is the mapping of the temperature anisotropies in the cosmic microwave background over a wide range of angular scales. Bringing all of these developments together we find that many aspects of the overall picture fit together remarkably well, giving us confidence in the validity of the whole cosmological framework. Others still provide challenging puzzles, particularly the unexplained dispersion in the local determinations of D/H and the very low abundance of ^{7}Li in some of the oldest stars of our Galaxy. But I am optimistic that we will not have to wait another three decades to iron out these remaining wrinkles in our understanding of the abundances of the light elements.

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References

Adams, T. F. 1976, A&A, 50, 461
Bonifacio, P., et al. 2002, A&A, 390, 91
Burles, S., Nollett, K. M., & Turner, M. S. 2001, ApJ, 552, L1

Coc, A., Vangioni-Flam, E., Descouvemont, P., Adahchour, A., & Angulo, C. 2004, ApJ, 600, 544
Crighton, N. H. M., Webb, J. K., Ortiz-Gil, A., & Fernandez-Soto, A. 2004, MNRAS, submitted (astro-ph/0403512)
D'Odorico, S., Dessauges-Zavadsky, M., & Molaro, P. 2001, A&A, 368, L21
Edmunds, M. G. 1994, MNRAS, 270, L37
Ellison, S. L., Songaila, A., Schaye, J., & Pettini, M. 2000, AJ, 120, 1175
Hébrard, G. & Moos, H. W. 2003, ApJ, 599, 297
Izotov, Y. I. & Thuan, T. X. 1998, ApJ, 500, 188
Kirkman, D., Tytler, D., Suzuki, N., O'Meara, J. M., & Lubin, D. 2003, ApJS, 149, 1
Levshakov, S. A., Dessauges-Zavadsky, M., D'Odorico, S., & Molaro, P. 2002, ApJ, 565, 696
Oke, J. B. & Korycansky, D. G. 1982, ApJ, 255, 11
Olive, K. A., & Skillman, E. D. 2004 (astro-ph/0405588)
Olive, K. A., Steigman, G., & Skillman, E. D. 1997, ApJ, 483, 788
O'Meara, J. M., Tytler, D., Kirkman, D., Suzuki, N., Prochaska, J. X., Lubin, D., & Wolfe, A. M. 2001, ApJ, 552, 718
Ostriker, J. P. & Tinsley, B. M. 1975, ApJ, 201, L51
Page, L., et al. 2003, ApJS, 148, 233
Pagel, B. E. J. 1997, Nucleosynthesis and chemical evolution of galaxies (Cambridge : Cambridge University Press)
Peimbert, M., Peimbert, A., Luridiana, V., & Ruiz, M. T. 2003, in ASP Conf. Ser. 297, Star Formation Through Time, ed. E. Perez, R. M. Gonzalez-Delgado, & G. Tenorio-Tagle (San Francisco: ASP), 81
Pettini, M. & Bowen, D. V. 2001, ApJ, 560, 41
Pettini, M., King, D. L., Smith, L. J., & Hunstead, R. W. 1997b, ApJ, 478, 536
Pettini, M., Smith, L. J., King, D. L., & Hunstead, R. W. 1997a, ApJ, 486, 665
Pinsonneault, M. H., Steigman, G., Walker, T. P., & Narayanan, V. K. 2002, ApJ, 574, 398
Prantzos, N. & Ishimaru, Y. 2001, A&A, 376, 751
Prochaska, J. X. & Herbert-Fort, S. 2004, PASP, 116, 622
Rogerson, J. B. & York, D. G. 1973, ApJ, 186, L95
Romano, D., Tosi, M., Matteucci, F., & Chiappini, C. 2003, MNRAS, 346, 295
Ryan, S. G., Beers, T. C., Olive, K. A., Fields, B. D., & Norris, J. E. 2000, ApJ, 530, L57
Sembach, K. R., et al. 2004, ApJS, 150, 387
Spergel, D. N., et al. 2003, ApJS, 148, 175
Steidel, C. C. & Sargent, W. L. W. 1987, ApJ, 313, 171
Steigman, G. 2004, in The Local Group as an Astrophysical Laboratory, (Cambridge : Cambridge University Press), in press (astro-ph/0308511)
Tosi, M., Steigman, G., Matteucci, F., & Chiappini, C. 1998, ApJ, 498, 226
Tytler, D., Fan, X.-M., Burles, S., Cottrell, L., Davis, C., Kirkman, D., & Zuo, L. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin:Springer-Verlag), 289
Tytler, D., et al. 2004, ApJ, in press (astro-ph/0403688)
Wood, B. E., Linsky, J. L., Hébrard, G., Williger, G. M., Moos, H. W., & Blair, W. P. 2004, ApJ, 609, 838